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Maximizing Sustainability: The Application of Digital Twins in Circular Economy Practices

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Abstract: With the growing focus on sustainability, the use of Digital Twins (DTs) to facilitate sustainable actions has shown immense potential, aiding waste management, resource optimisation, product design, cost savings, and maintenance. Digital Twin in Circular Economy can enhance information and material flows by improving transparency and traceability. This paper analyses and discusses the application of DT technology in the Circular Economy, focusing on its functions, architectural configurations, and use cases. This work shows how DT-based solutions support circular practices across multiple sectors to achieve sustainability outcomes.

Keywords: Digital Twin; Circular Economy; sustainability; Industry 4.0; waste management

1. Introduction

The Circular Economy is a sustainable-driven model for production and consumption that contrasts with the traditional linear economy, which follows a “take–make–dispose” pattern [1,2]. Consequently, the objective of the Circular Economy is to maximise the value and time of resources and minimise associated waste [3]. As a result, the concept of the Circular Economy has gained increasing attention in recent years as a pathway for sustainable natural resource management, focusing on optimising resource consumption, preventing waste, and promoting material reuse [4,5]. The transition to a Circular Economy is perceived as a crucial step in addressing economic growth, environmental issues, and resource scarcity. Furthermore, the Circular Economy has emerged in response to the global depletion of natural resources and the need to address growing environmental challenges [6]. The Circular Economy business model is an innovative approach grounded in core circular principles. It can have different starting points but always aims to address environmental and social challenges while also generating economic value [7,8].

The term “Circular Economy” was first proposed by Pearce et al. [9] in a study exploring the relationship between the environment and the economy [8]. It was evident that the main goal of a Circular Economy is to substitute the end-of-life stage of products in their lifecycle with product recovery strategies such as repurposing, remanufacturing, and recycling [10–13]. Hence, a Circular Economy enables greater resource optimisation [14] and promotes sustainable production and consumption [15–17]. In general, the Circular Economy has been defined in various ways as the concept has gained increasing attention from researchers across multiple disciplines [18,19]. For instance, Kirchherr et al. [19] defined the Circular Economy as a system based on business models that aim to accomplish sustainable development and can replace the end-of-life stage through reusing, recovering, recycling, and reducing materials while operating at either micro, meso, or macro levels. Other definitions describe the Circular Economy as a strategy that would convert goods at their end-of-life stage into resources for others, allowing waste minimization [20–22]. Based on these definitions, it is evident that a Circular Economy contributes to economic



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growth [23], promotes sustainability [24,25], reduces emissions [26], promotes resource efficiency [27,28], and preserves natural resources [29,30]. In addition to these contributions, Circular Economy strategies play an effective role in advancing sustainable development goals across the European Union (EU). Alnafrah et al. [31] highlight progress toward SDG 12 and SDG 13, while showing that the impacts of Circular Economy initiatives vary depending on the level of sustainable development achieved and differ between northern and southern European countries. Moreover, it is clear that the idea of Circular Economy draws from various theoretical frameworks, such as ecological economics, environmental economics, and industrial ecology. Its implementation involves different approaches at different levels: on the micro-level, it involves incorporating cleaner production techniques and eco-design; at the meso-level, it involves establishing eco-industrial parks; and at the macro-level, it includes initiatives such as waste minimization programs, energy-efficient cities, and promoting high-quality consumption [32].

Information is the main facilitator for the successful execution of the Circular Economy. Nonetheless, some information might be lost or hard to retain throughout the lifecycle stages of a product [33,34]. As a result, it is advantageous to employ digital technologies to facilitate accurate acquisition of information throughout the full lifecycle of a product. Based on this information, the employed digital technology can send instructions related to the recycling, repairing, or reusing of materials [35,36]. Hence, the main function of digital technologies is to analyze the obtained information and then make a decision based on this analysis. Moreover, digital technologies enable more accessible and transparent access to information, enhancing the process of decision-making [37]. In general, digital technologies assist in creating a Circular Economy with enhanced information exchange and data acquisition of the product's location, condition, and availability [38,39]. The Digital Twin (DT) technology has shown significant potential for assessing the information discrepancy in the Circular Economy.

DT technology can efficiently track the flow of materials throughout the full lifecycle of a product by creating a dynamic information network [40]. Due to the numerous advantages of DTs, researchers are attempting to apply them in several fields. Consequently, many scholars strived to explore the DT technology [41–43]. For example, based on Semeraro et al. [44], the concept of a DT involves creating a virtual system that replicates the behavior of a physical system and updates itself in real-time based on data received throughout its life cycle. As the DT emulates the physical system, it can estimate potential issues and chances for optimization and suggest real-time solutions to mitigate unexpected events. Ultimately, the goal is to improve the physical system's performance by closely monitoring and assessing its operating profile. DT technology can also be defined as computer-based models that simulate, emulate, or mirror the behavior of a physical entity [45,46]. Initially, the first definition of the DT was offered by NASA in 2012 [47] where it was characterized as a comprehensive probabilistic simulation that operates across multiple scales that can continuously forecast an area of choice. In general, a DT creates a digital replica of a physical asset, process, or system [48–50]. DT technology displays the inherent state of the physical system by using both simulation and modeling techniques [46]. A DT is mainly characterized by the physical, network, and digital layers [44]. The physical layer consists of the physical system and its processes; the digital layer contains the digital models, simulations, and algorithms that are utilized to develop a digital replica of the physical system [51]; and the network layer connects the physical layer to the digital layer to enable a continuous flow of data, information, and knowledge [52–54]. Circular Economy and Digital Twin together can enhance industrial sustainability. The Digital Twin replicates physical systems, enabling real-time monitoring, prediction, and prescription. The Circular Economy reduces waste and extends product lifecycles. The integration of DT into the Circular Economy supports material traceability, decision-making, waste management and resource efficiency.

The use of DT technology in the Circular Economy is rapidly expanding as Industry 4.0 and 5.0 paradigms are continually explored, demonstrating the potential to enhance the effectiveness of Circular Economy practices. As the application of DT in the Circular Economy is further investigated, various literature reviews have emerged to investigate and illuminate its influence. For instance, Popescu et al. [55] carried out a literature review to explore the impact of DT on sustainability. The authors proposed a functional DT solution for sustainable manufacturing based on the literature review outcomes. Chen et al. [56] reviewed existing literature with a focus on the use of DTs to aid the Circular Economy in remanufacturing construction waste. Similarly, Lui et al. [57] formed a literature review that explores the research advancement and trends of the integration of the Circular Economy and digital economy. In the same way, Han et al. [58] clarified how digital technologies, including DTs, can enhance the Circular Economy's performance throughout the stages of a product's lifecycle. Likewise, Terenzi et al. [59] summarized the effects of DTs on the Circular Economy through case studies and examples presented by various researchers in multiple fields. Although several literature reviews have examined the role of DT technology in sustainability and Circular Economy contexts, most existing studies adopt either a sector-specific perspective or a predominantly conceptual viewpoint. Prior reviews focus on single-sector applications without comparing DT architectures and functional components. As a result, the architectural dimension of DTs is often treated at a high

level of abstraction. Moreover, existing reviews do not link DT functions and architectural choices to Circular Economy levels: micro, meso, macro and lifecycle stages. For this reason, this review explicitly addresses this gap by providing a cross-industry, architecture-centred synthesis of DT applications for the Circular Economy.

This review aims to provide an industry-specific overview of how DT technology is utilized to support Circular Economy principles across various industries. Furthermore, this paper discusses the DT functions and architecture in each industry. Consequently, the main research questions addressed in the paper are as follows:

- RQ1: In which application contexts are Digital Twin technologies employed to support Circular Economy practices?
- RQ2: What functions do Digital Twins perform in enabling Circular Economy activities?
- RQ3: How are Digital Twin architectures structured to support Circular Economy implementation?

The research questions cover various aspects, including the contextual analysis of DT applications in the Circular Economy, the functions provided by DT in each application, the architecture and components of DT systems that support Circular Economy principles, and the research challenges associated with their implementation. These factors have been thoroughly examined in order to establish and investigate the essential characteristics and difficulties in constructing the DT technology for supporting the Circular Economy. The content in this paper is structured as follows: the applications of the DT in the Circular Economy are shown in Section 2. DT functions and architecture are discussed in Sections 3 and 4, respectively. Meanwhile, the conclusion and research challenges are presented in Sections 5 and 6, respectively.

2. Research Methodology

This study adopts a Systematic Literature Review (SLR) methodology using PRISMA framework as shown in Figure 1. The main elements of the search strategy, databases, timeframe, and selection criteria are summarized in Table 1. The literature search was conducted using five major scientific databases: Scopus, Web of Science (WoS), IEEE Xplore, ScienceDirect, and Google Scholar for the timeframe: September 2010- November 2025.. The primary search strings included: “Digital Twin” AND “Circular Economy”, “Digital Twin” AND “Sustainability”, and “Digital Twin” AND (“Industry 4.0” OR “Industry 5.0”) AND “Circular”. The selection of studies followed clearly defined inclusion and exclusion criteria. Publications were included if they:

- (i) were peer-reviewed journal articles or international conference proceedings,
- (ii) were written in English,
- (iii) explicitly addressed the application, function, or architecture of DT technology, and
- (iv) established a direct link between DTs and Circular Economy practices.

The screening process was carried out in multiple stages. First, duplicate records retrieved from different databases were removed. Second, the remaining studies were screened based on their titles and abstracts to eliminate irrelevant publications. Third, full-text screening was conducted to assess eligibility against the inclusion criteria. After duplicate removal, 210 publications remained. Following title and abstract screening, 136 articles were excluded for irrelevance, leaving 74 full-text articles for eligibility assessment. After full-text evaluation, 32 articles were excluded due to insufficient linkage between DT applications and Circular Economy practices. Consequently, 42 studies were retained for in-depth qualitative analysis. For each selected study, structured data extraction was performed to capture information related to: (i) industrial application context; (ii) Circular Economy level (micro, meso, macro); (iii) Circular Economy activities (reuse, recycling, remanufacturing); (iv) DT functions; and (v) DT architecture and components. Figure 1 shows the PRISMA flow diagram with all steps and defined criteria.

Table 1. Summary of the systematic literature review methodology.

Search Component	Description
Databases	Scopus, Web of Science, IEEE Xplore, ScienceDirect, Google Scholar
Search fields	Title, abstract, and keywords
Time span	2010–2025
Core keywords	“Digital Twin”
Combined keywords	“Circular Economy”, “Sustainability”, “Industry 4.0”, “Industry 5.0” (“Digital Twin” AND “Circular Economy”),
Example search strings	(“Digital Twin” AND “Sustainability”), (“Digital Twin” AND (“Industry 4.0” OR “Industry 5.0”) AND “Circular”)
Language	English
Document types	Peer-reviewed journal articles and conference proceedings
Final studies included	42

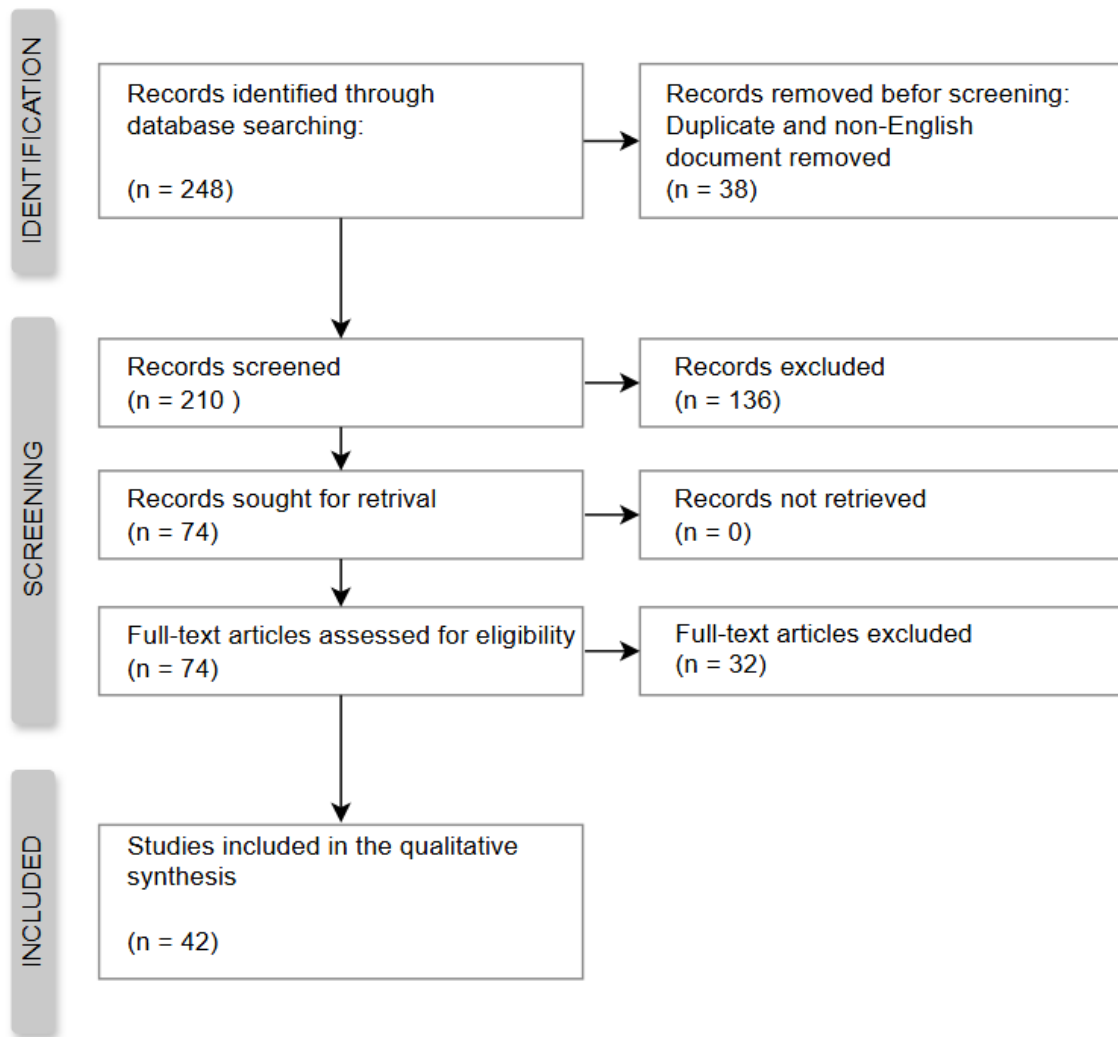


Figure 1. PRISMA flow diagram.

3. Results of the SLR

3.1. Industrial Applications of the DT in the Circular Economy

The existing DT applications are “weak circularity-oriented”, where Circular Economy strategies focus on efficiency improvements, waste reduction, reuse, and recycling within existing production and consumption structures. Instead, “strong circularity” emphasises systemic transformations, including product redesign, dematerialisation, servitization, and the transition to product-as-a-service and performance-based business models.

DT applications for promoting the Circular Economy are presented across various industries. One of the main uses of DTs is for data collection, data traceability, and decision-making. Moreover, the DT is used to manage information in the Circular Economy, influencing recycling decisions and information exchange throughout the lifecycle of a product [36]. The DT is also developed to focus on waste management in order to extend a product’s lifespan. DT applications in the Circular Economy are identified at three main levels, namely, the micro-level, meso-level, and macro-level. At each level, the DT is developed to provide specific functions, such as optimization, fault detection and diagnosis, and optimization [36,60]. In addition to these levels, the DT architecture is applied across various industries to support and enhance their Circular Economy. These applications span multiple industrial sectors, including manufacturing/production, construction, and photovoltaic systems, while supply chain-oriented DTs function as cross-cutting frameworks that connect and coordinate activities across these sectors. This section comprehensively assesses these applications to address the first research question. Figure 2 shows the number of papers published in each application context. The distribution of DT applications across industries reveals clear sectoral patterns. Among the 42 selected studies, manufacturing and production account for the largest share, representing more than half of the published work, followed by construction, supply chain, and photovoltaic applications. This dominance reflects the strong alignment between DT capabilities—such as

real-time monitoring, predictive maintenance, and process optimisation—and the sustainability challenges faced by manufacturing systems. In contrast, applications in supply chains and photovoltaics remain comparatively limited, indicating emerging but underdeveloped research areas.

The analysis of the different application domains addresses RQ1 by identifying the industrial contexts in which Digital Twin technologies are currently applied to support Circular Economy practices.

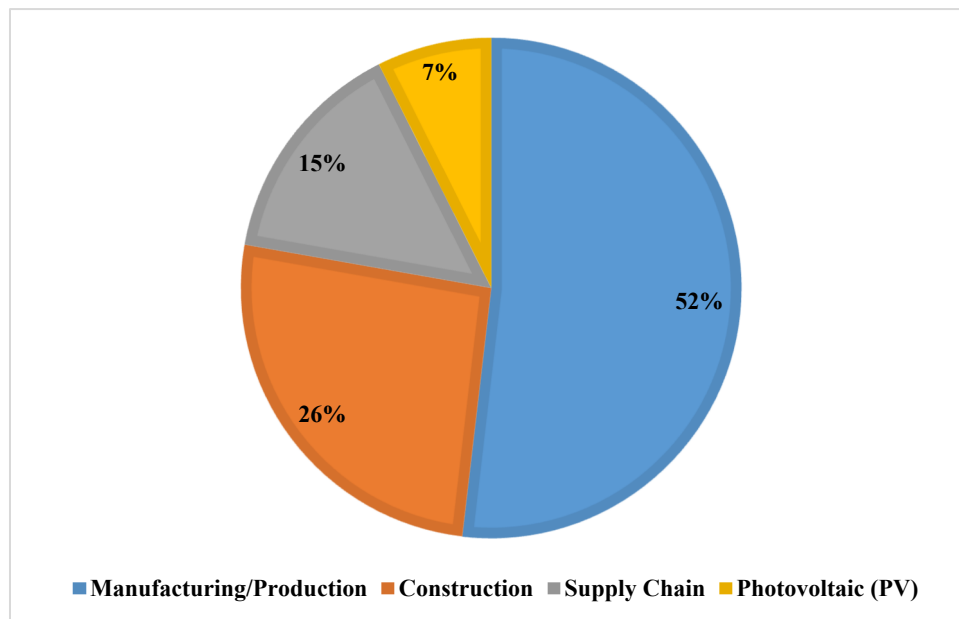


Figure 2. Distribution of DT applications across industrial sectors and cross-sectoral supply chain contexts within Circular Economy research.

3.1.1. DT for Circular Economy in Manufacturing/Production

DT technology is considered revolutionary in the manufacturing industry, providing a digital replica of physical assets and processes. The purpose of this technology in promoting the Circular Economy of the manufacturing industry is to improve waste management, resource utilization, data collection, and cost savings [59]. The main advantage of employing digital technologies, such as DT, in promoting the Circular Economy in the manufacturing industry is the application of data analytics, which provides tangible benefits in achieving the required environmental objectives [61]. Consequently, researchers strived to apply DT technology to enhance the Circular Economy of the manufacturing industry. For example, DT technology is used to create flexible Circular Economy-based de- and re-manufacturing systems [62]. Consequently, the DT was capable of enhancing operations management and data synchronization of the proposed circular factory.

Another application of the DT is to provide an enhanced understanding of the product or process, thus, facilitating the implementation of Circular Economy principles within the manufacturing industry. This was reflected in various published papers. For instance, according to Lawrenz et al. [63], sustainable product creation is the primary driver of the Circular Economy. In order to attain this, a DT sandbox can be employed to facilitate the collection and exchange of data between different Circular Economy entities, thereby influencing decisions related to material selection, design, and production. In a similar direction, Alves et al. [64] promoted the Circular Economy at both the micro-level and macro-level through waste management in the clothing industry. DT technology has been used for product traceability and the collection and storage of fundamental information. The authors also stressed the importance of the DT in implementing the Circular Economy and ensuring product traceability.

Other researchers utilized the DT technology to enhance product traceability in a manufacturing/production plant. For example, Carlsson et al. [65] proposed a framework that uses a QR code linked to a product's DT to simultaneously capture and update information. The DT enables automatic product tracking, at the same time, it collects information in real-time. Accordingly, the DT is able to evaluate the environmental effects induced by the product throughout its lifecycle. Moreover, the DT enhances data transparency by storing and providing relevant information to users and stakeholders, improving the understanding of how to sustainably maintain, use, refurbish, dismantle, and recycle the product. In contrast, Kutscher et al. [66] focused on building a DT of the machine that is used for producing components/parts of the products. The authors proposed using the DT technology to virtually test the software of a machine. The DT was able to extend the lifespan of the machine, embed new features in the

machine, and make decisions associated with the disposal of the machine. In a similar way, Pehlken et al. [67] used DT technology for cascading materials and urban mining to increase production efficiency. The DT was developed to improve information sharing between manufacturers and recyclers to enhance the sustainability of the manufacturing processes. This approach shows potential for resource savings and highlights the complexity of end-of-life resource management. The DT is updated continuously with product and material structures along with pertinent material and energy movements, but limitations in technology and system complexity exist. The available literature mostly offers conceptual frameworks and lacks technical details on the DT's architecture [68]. In contrast to the limited focus on the DT architecture found in other papers, Rocca et al. [69] presented a comprehensive framework for the DT in the Circular Economy. Their proposed DT focuses on electrical and electronic equipment in a plant and aims to optimize resource use to increase the sustainability of the production processes. The DT is designed to monitor and control a manufacturing system's real-time disassembly process, allowing for real-time decision-making. The authors chose the Process Control Unified Architecture (OPC-UA) communication protocol to enable communication between the industrial equipment and the system and to enable immediate collection and control of data, along with the creation of a virtual replica of the system. In order to manage the information flow, the authors employed widely-used numerical computing and engineering tools like MATLAB and SimuLink. Furthermore, they established a real-time connection with the workstations by leveraging the OPC-UA toolbox provided within MATLAB, which allows for direct access to live and historic data. Similarly, Kerin et al. [70] discussed the architecture of a DT applied to enhance the manufacturing industry's Circular Economy in detail. The authors proposed a multi-level DT prototype for a large industrial engine, which integrates a product and process overview to automate decision-making for remanufacturing. The DT represents the physical product in a virtual space. The DT allows the simulation of various scenarios, providing valuable data for the decision-making module. The prototype is developed via a Raspberry Pi Zero W microcontroller board linked to sensors that capture environmental conditions, location, and available product performance information. The collected data is combined to simulate a digitally connected product. The Bees Algorithm is then applied to identify the optimal disassembly sequence and component routing, thereby optimizing the decision-making process. In the same way, Čech et al. [60] proposed model-based simulation and DT that describe the theoretical behavior of a system and its surrounding environment based on analyzed sensor data. The DT is exploited to assess and simulate multiple scenarios to support decision-making. Similarly, Zacharaki et al. [71] proposed a DT to diagnose machinery faults and extend the machine's lifetime. The authors created a simulation engine that optimizes maintenance activities by monitoring and predicting the machine's performance, preventing failures and production line stoppages. The DT is made of three parts, which correspond to the physical, network, and digital layers. The physical layer has a three-stage IoT infrastructure that uses existing wireless sensors for data acquisition, sensor data aggregation systems that convert analog data into digital data, and IT functions and modules that pre-process the data. Historical data, lifecycle data, business model data, and digital retrofitting data are used and preserved for later use in data analytics algorithms. The network layer includes manufacturing industries, user interfaces, European Remanufacturing Network (ERN), and maintenance-supportive companies. A refurbishment and remanufacturing framework, repair data analytics, and decision support framework are utilized at the digital layer. These studies indicate the uses of the DT technology in the manufacturing industry for flexible de- and re-manufacturing operations, machine lifespan extension, product traceability, and resource efficiency. Consequently, DT technology has emerged as a revolutionary technology in the manufacturing industry for promoting its Circular Economy by enhancing the management of waste, utilization of resources, and collection of data. Despite these advantages, there is still a need for further development and technical details of the DT architecture in the manufacturing industry to promote its Circular Economy.

3.1.2. DT for Circular Economy in Construction

The utilization of DT technology in the construction industry holds the promise of transforming it by promoting environmental sustainability and implementing a Circular Economy approach [72]. The DT allows for materials and resources to be recycled and reused throughout their lifecycle; they can remain in use for as long as possible. Furthermore, a DT can simplify the construction design process [73]. The DT can be helpful in the field of geotechnics, as it can aid in constructing not only a physical asset but also in meeting the needs of end-users and the community [74]. Due to these advantages, various researchers have developed the DT to improve the economic circularity of the construction industry. A decentralized and sustainable DT is proposed by Teisserenc et al. [75] to aid circularity in BECOM (building, engineering, construction, operations, and mining) activities, considering that material waste is a huge hurdle for the BECOM industry. DT technology promotes the Circular Economy by improving material traceability and facilitating the reuse and recycling of materials [76]. In their

decentralized and sustainable DT cycle model, the authors emphasize the integration of blockchain technology with DT technology to support BECOM activities. Similarly, Xie et al. [77] highlight that blockchain-based innovation systems can enhance sustainability by improving data traceability, security, and supporting circular practices. Their proposed DT model takes data from the information value chain, while blockchain technology enhances information sharing, management, traceability, and security. The model consists of four architectural layers: connection, data management, computing, and blockchain layers. The connection layer extracts data from the BECOM project through software APIs, middleware, IoT devices, and RFID. The data management layer comprises user interfaces that enable project users to engage with the DT system. The blockchain layer handles key historical data executed with DT applications through blockchain ledgers.

Additionally, Teisserenc et al. [72] proposed another innovative theoretical framework for environmentally conscious blockchain-powered DTs. The authors realized that Building Information Modeling (BIM), IoT, and DTs are considered the main enablers of digitalization of the construction industry. The authors reported that a sustainable blockchain DT shows the potential to improve environmental sustainability in the construction industry. Where the DT can be used to allow stakeholders to take part in a decentralized Circular Economy. Furthermore, the study showed that the main non-functional requirements essential for a DT in the construction industry include data privacy, security, interoperability, integrity, storage, and ownership. The role of blockchain technology is to guarantee the integration of accurate data into the DT, as data security is highly essential for designing a DT. Seven dimensions are used to illustrate the DT framework, depending on the project lifecycle. The first dimension focuses on design data, graphical and non-graphical information, and 3D models. The second dimension acquires construction data, scheduling data, and visualization. The third dimension is cost, which includes financial data relevant to the project. The fourth dimension is related to maintenance and includes IoT management. The fifth dimension is the sustainability dimension which contains data related to the Circular Economy and waste generation. The sixth dimension is about safety and includes risk management and safety regulations. All these dimensions lead to the seventh, which is the contractual dimension.

Some research studies were carried out to focus on improving the circularity of construction materials through DT technology. For example, Züst et al. [78] suggest recycling demolition waste from construction materials as a strategy due to the significant environmental impact of such waste. The process of reusing these materials can lead to reduced demand for materials, transportation, and landfill sites. The authors highlight the importance of understanding the system's behaviour to promote the circular use of construction materials and suggest that a DT of the steady-state dynamics of the system would be useful in achieving this goal. Furthermore, the DT can be utilized to model the excavation and demolition material flow in the region. The DT is employed to replicate the system's current steady-state dynamics, offering a generic decision-making model which aids in the efficient transfer of materials. Other researchers focused on designing the DT to enhance buildings' Circular Economy. For example, O'Grady et al. [73] demonstrate how to enhance the economic circularity of building components by disassembly and reuse. The authors emphasize the important role that the DT can play in enabling practitioners and designers to visualize construction details and develop integrated designs aimed at minimizing waste. Hence, a DT is developed to prove the concept of reuse and disassembly, with several strategies for the Circular Economy being implemented, including reducing construction waste, integrating waste into new usable components, reusing replacement parts, designing for lifetime extension, and reusing and recycling construction materials, homes, and areas to avoid depletion of natural resources and pollution. Consequently, the authors created a BIM-based DT of a building. The authors prove that the application of DTs in virtual reality environments, with the help of BIM, can enhance the Circular Economy of buildings. The BIM model is merged into a Virtual Reality (VR) engine to get a complete digital view of the physical characteristics of the building. The model can offer a geometric representation of the building, allowing users to navigate through the environment and showing what can be recycled, as well as providing reasoning behind the design details and environmental sustainability advantages of the building project.

Moreover, Çetin et al. [79] proposed creating three different DTs to assist with various Circular Economy goals and pilot projects related to building stock. These projects focus on different stages of the building lifecycle, including demolition or new construction, renovation, and maintenance. The authors emphasize the importance of incorporating circularity into the construction of buildings to emphasize the reuse of building materials. The primary goal of the DT, in this case, is to improve the work processes, data access and sharing, as well as simplify the maintenance operations. The three different DTs proposed by the authors generate a model of an entire building stock using scanning technologies, drones, BIM, Artificial Intelligence, and image recognition technologies for digitalizing architectural drawings. In addition to buildings, other researchers designed the DT technology to enhance the Circular Economy of railways. Accordingly, Kaewunruen [80] used a railway bridge as a case study to exemplify how a DT can be employed in construction maintenance. The author highlighted that the application

of the DT for Circular Economy management could be beneficial in construction maintenance, where the DT can be utilized to assess greenhouse gas emissions and cost consumption and also to facilitate virtual collaboration among stakeholders involved in construction, operation, and maintenance. The DT can then control the condition of the bridge as well as locate any damages, gather data via sensors, visualize data among stakeholders, prioritize maintenance decisions, create virtual collaborations, allocate the needed amount of materials for maintenance activities, and assist engineers in quantifying life cycle costs as well as greenhouse emissions. The applications of DT technology in the construction industry can revolutionize the sector by enhancing environmental sustainability and promoting its Circular Economy. The DT technology enhances the recyclability and reuse of materials and components; this, in return, simplifies the construction design process.

3.1.3. DT for Circular Economy in Supply Chain

Unlike sector-specific applications, supply chain-oriented Digital Twins are inherently cross-cutting, as they operate across multiple industries and lifecycle stages rather than within a single domain. Their primary role is to enable integration and coordination among manufacturing, construction, and energy systems by facilitating real-time data exchange, product traceability, and decision-making across the entire value chain. Therefore, supply chain DTs should be understood as horizontal enablers of Circular Economy practices rather than as an independent industrial sector [81]. In this study, supply chain applications are explicitly treated as cross-cutting Digital Twin systems that integrate multiple industrial domains, rather than as a separate sector, ensuring conceptual consistency in the analysis. Nevertheless, implementing a DT can enhance transparency and trust across the various stages of the supply chain, including recycling and remanufacturing processes. Moreover, the DT optimises supply chain processes, facilitates the acquisition and provision of pertinent information at keypoints in the cycle, and promotes greater collaboration throughout the cycle [36]. Furthermore, the DT can facilitate the visualisation of design parameters, alterations, and changes in the product's condition. Upon transmitting and evaluating sensor data in real-time, the virtual replica can be continuously updated. This information can be shared among different supply chain processes and stakeholders throughout the product's entire life cycle.

Based on the available literature, the number of publications related to the applications of DTs to improve the Circular Economy of supply chain processes is limited. Nevertheless, several researchers discussed services provided by the DT for the Circular Economy of the supply chain. According to Pehlken et al. [81], better Circular Economy strategies need to be implemented for scrap tires, and the use of recycled rubber can reduce stress on virgin rubber. The authors suggest that a DT that records the tire material composition and tracks its usage throughout its life span would benefit tire recyclers. Other researchers explored the use of the DT for facilitating the decision-making process related to the recycling processes. For instance, Mangers et al. [82] proposed a DT that can leverage knowledge to serve as a decision-support tool for product designers. The authors aim to promote a circular resource flow by aligning product design with end-of-life information through a reflective process. This approach enables designers to consider user requirements and information regarding the end user and end-of-life process chains during the product design phase. The authors utilized circular value stream mapping to collect end-of-life data for PET bottles. The end-of-life information is processed using a digital state flow representation and then transferred into the DT to simulate different scenarios. The authors emphasize that the simplified state flow of the packaging waste can be seen as an advantage of the DT. Once the DT has been provided with accurate data obtained from value stream mapping at both organizational and supply chain levels, individuals may utilize the DT without requiring knowledge of specific company procedures. Similarly, Kalaboukas et al. [83] introduced the concept of cognitive DTs, which were applied in agile supply chains for waste flow monitoring and optimization. The DTs were used to share information about the supply chain system's current and anticipated waste supply. However, the authors noted that having an independent DT is insufficient to fully comprehend the complexities and requirements of supply chain dynamics. They suggest using interconnected cognitive DTs in supply chain dynamics, as they possess cognitive abilities that can detect, predict, and understand different observed behaviors at an early stage. A network of interconnected DTs collects information about behavior through sensors, systems, other cognitive DTs, or external data sources. The collected data is then mapped against a behavioral model to create new knowledge. Existing behavior models or data-driven expertise are utilized to update DTs and predict potential future failures. Once an incident or trend is identified, a simulation based on root-cause analysis of the cognitive DT's future behavior is presented, along with predictions of potential future failures. Following simulation and prediction, optimization services suggest improvements through a feedback loop, and actuation services send messages to physical assets to alert behavior accordingly. In addition, the DT can optimize and forecast the tracking and management of returned products that are no longer in use.

The application of DT technology in the supply chain enhances the efficiency and transparency of the Circular Economy by attaining real-time data, promoting collaborations, optimizing processes, and increasing the visibility and transparency of the supply chain process. Furthermore, DT technology increases the accuracy of collected data and supports the decision-making process associated with recycling activities. However, additional research is needed to find the full potential of using DT technology to enhance the Circular Economy of the supply chain industry.

3.1.4. DT for Circular Economy in Photovoltaics

The adoption of the DT concept for PV systems offers significant potential to improve operations, predictive maintenance, and energy efficiency, but faces several challenges. These include the availability and quality of real-time data, which is essential for accurately synchronizing the DT with its physical counterpart; the lack of adequate sensors or the presence of noise or missing data can compromise the accuracy of the models [84]. The challenge of integrating with existing systems and interoperating across protocols, hardware, monitoring systems, and legacy software represents organisational and technical barriers that must be overcome for the effective deployment of DTs in PV.

There is limited research conducted on the applications of DT technology to support the Circular Economy in the PV industry. However, Hernandez et al. [84] propose advancing a DT for a PV plant to enable efficient data management and achieve sustainable, eco-friendly end-of-life management of PV panels. The DT encompasses a parameterized digital depiction of the PV panel from inception to end-of-life, which can simulate its real behavior. The 3D geometry of the PV system is developed using CAD design software and 3D drone mapping. Wireless sensor networks such as Narrow Band-Internet of Things (NB-IoT/5G) can be used for monitoring, with electrical string boxes, sensors, production meters, and inverters transmitting data to the NB-IoT network for a monitoring portal. Individual IoT modems are utilized to connect sensors through RS-485 serial ports, and the modems can be used as converters from Modbus protocol to Narrow Band IoT.

Additionally, Bartie et al. [85] developed an intricate DT of a silicon PV system. The simulation offers results that can establish system configurations, enabling resource conservation and increased sustainability. The authors introduced a DT simulation model to depict the life cycle of a crystalline silicon (c-Si) PV. Process simulation is proposed to anticipate the behaviour of the system to variations in input parameters as it enables detailed analysis which complies with the laws of conservation and the second law of thermodynamics at every step. The entire lifecycle is simulated by incorporating large databases of minerals, metals, and other compounds' physical, chemical, and thermodynamic properties. The authors employed Neural Networks (NN) to pursue a non-linear life cycle simulation approach since NN can be beneficial to model complex systems' input and output relationships. In order to generate a code that can initiate, train, test, and validate the networks, MATLAB's NN user interface was utilized to provide a code that executes such actions. In addition, an individual single-output NN is created for other dependent variables of interest.

The limited research conducted on the applications of DT technology in the PV industry did not hinder the promise it showed for sustainable management of PV panels and resource conservation. Furthermore, DT technology provides efficient data management, thorough analysis of the system, and simulation of its behaviour. These benefits lead to sustainable management of a product's end of life stage. However, there is still a need to explore the potential of the DT technology in the PV industry for promoting the Circular Economy.

4. DT Applications in Circular Economy Levels and Activities

The use of DTs to promote Circular Economy practices can have different architectural components and functions. However, the main goal of leveraging DTs to improve sustainability and support Circular Economy principles remains consistent across various industries. One common advantage of DTs in the Circular Economy across all industries is their ability to collect information and automate decision-making processes for waste management. This section discusses in detail the main functions and architecture of DTs based on the available literature. The literature demonstrates applications of the DT across different levels of the Circular Economy and Circular Economy activities. Table 2 summarizes the applications of using the DT for promoting the Circular Economy, the DT's main functions, the Circular Economy levels, and the Circular Economy activities used. Such classification helps identify the reoccurring trends and benefits of using the DT to promote the Circular Economy in different applications. The subsequent sections discuss these elements in detail.

Table 2. DT functions and Circular Economy activities applied at each lifecycle stage, Circular Economy level, and application.

Application Context	CE Levels	CE Activities	DT Function	Reference	
Manufacturing/Production	Micro	Reusing and Recycling	Support the realization of reconditioning systems.	[62]	
			Data collection and storage, operation monitoring, real time analysis, and execution of data analytics.	[69]	
			Collect data and automate decision making for remanufacturing.	[60]	
			Facilitate decision-making in water processing and operations, reduce operational expenses such as chemical usage and energy consumption, mitigate the risk of untreated wastewater leaks, and enhance data gathering in water waste management.	[86]	
			N/A	Describe the theoretical behavior of the system and its surrounding environment for machine performance optimization.	[70]
	Macro	Reusing and Recycling	Collect and exchange data among the individual Circular Economy entities for the creation of sustainable products.	[63]	
	Macro & Micro	Recycling	Improve waste management in the textile and clothing by capturing data across the entire lifespan of the product and improve its traceability.	[64]	
	Construction	Micro	Reusing and Recycling	Capturing data and enhance material traceability.	[75]
				Improve efficiency, data sharing, collaboration, sustainability, and information security.	[72]
				Replicate a system's current steady-state dynamics and offer a decision-making model.	[78]
Create a geometric representation building structure, facilitate decision making on what material to recycle, as well as provides the rationale behind the specific design elements and advantages of the building project.				[73]	
Generate a model of an entire building stock, create a detailed inventory of materials and reusable components, and identify surface defects as well as hazardous contents.				[79]	
Harmonize and transform the needs of end-users, the community, and the environment through behavioral analysis.				[74]	
Supply Chain	Macro	Reusing	Visualize a construction project and determine greenhouse gas emissions, and cost consumption, as well as generate virtual collaboration for contributing stakeholders.	[80]	
	Macro	Recycling	Monitor and optimize waste flows, as well as share information regarding the present or projected waste supply in the supply chain system.	[83]	
	Macro & Micro	Reusing and recycling	Track, manage, optimize, and forecast returned products that are no longer in use.	[36]	
		N/A	Offer a digital state flow representation and transfer collected end-of-life information to simulate different scenarios.	[82]	
Photovoltaic	Micro	Reusing and recycling	Create a geometrical model of a PV plant and simulate its behavior throughout its lifecycle.	[85]	
		Recycling	Simulate the life cycle of a PV module and model the input and output interrelationships for decision making.	[86]	

Frequency analysis of DT applications across Circular Economy levels in Table 2 shows a strong concentration at the micro level, particularly in manufacturing and construction contexts, where reuse and recycling activities dominate. Macro-level applications appear less frequently and are mainly associated with supply chain coordination and stakeholder-level decision-making. Notably, meso-level applications are almost entirely absent, confirming a significant research gap. Similarly, reuse and recycling account for the vast majority of DT-supported Circular Economy activities, while eco-design and remanufacturing are only marginally addressed.

Table 2 shows how Digital Twins support Circular Economy practices. Most applications are concentrated at the micro level, particularly in manufacturing and construction, where DTs are mainly used for monitoring, traceability, and decision support for reuse and recycling activities. In contrast, macro-level applications are less frequent and appear primarily in supply chain contexts, while meso-level implementations remain largely unexplored.

With the goal of determining the impact of DT applications on the Circular Economy, it is critical to identify the level of Circular Economy (micro, macro, and meso) where the application occurs. The DT is useful for data collection and visualization of products and systems to improve their circularity, especially at micro and macro levels. Most of the published papers focus on DT applications at the micro level, particularly in industries such as manufacturing, construction, and photovoltaics, where waste management and resource optimization are critical. Applications at the macro level are mainly found in the supply chain industry, showing the interrelationships within the supply chain [82], and some in manufacturing and construction, primarily for collecting data from stakeholders and individuals [64,80]. DT applications at the meso-level have not been extensively explored, leaving opportunities to develop frameworks for eco-parks or understand why DT applications may not be feasible at that level.

The DT can also be designed to carry out various Circular Economy activities to promote the circularity of different industries. Based on the conducted literature review, researchers focused only on reusing and recycling activities. The focus of the DT in these applications is to aid the decision-making process associated with reuse or recycling activities in the Circular Economy, contributing to the prerequisite processes needed to define the need for such activities, as well as the subsequent steps to implement them [36]. In the case of construction, materials used to build a project can be carefully chosen, and certain materials can also be identified for reuse or recycling purposes before demolition projects, as well as the area used can be reused, and the decision-making is eased using DTs [79]. However, none of the papers discussed the utilization of DTs in eco-design. Nonetheless, DTs can help in identifying materials or systems that may have environmental implications, which can be useful for future eco-design development [65]. In order to improve the longevity of a product's lifecycle, the Circular Economy typically focuses on the stages of a product's lifecycle. The DT is a prominent digital technology that can aid in achieving this goal. However, the applications of the DT can occur at specific intervals of the lifecycle or across all stages of the lifecycle. The typical lifecycle stages of any product are the beginning-of-life, middle-of-life, and end-of-life stages. The main functions provided by the DT at the beginning-of-life stage, prior to the design stage of a product, include design optimization and decision-making associated with the utilization of materials and natural resources [36]. These functions ensure the product's sustainability and circularity before its existence. This, in return, reduces the induced waste related to improper design and material choices [65]. Most often, the DT is seen to be applied at both the beginning-of-life and middle-of-life stages. This is facilitated to focus on extending the lifespan of a system or product. Even though the DT is applied throughout the lifecycle of a system or product, most of these applications focus on the end-of-life stage. DT applications at this stage focus on reusing a product or system and extending its use. This application helps in the decision-making process and behavioral analysis to determine whether the product or system can be retrieved at the end-of-life and can withstand additional reprocessing, such as remanufacturing, recycling, or reconditioning [62]. Furthermore, the DT can predict the possible timeframe or instance when the product or system reaches its end-of-life stage and facilitate necessary decisions for extending its useful life [70]. Applying the DT during the full lifecycle of a product or system can induce significant advantages, as it will provide a complete view and application of Circular Economy principles and activities. The DT can monitor the product throughout its entire lifecycle, capture lifecycle data, and exchange information with different stakeholders for traceability and assessment of the product's condition and impact [65]. The collected information can be used to improve product lifecycle management, reduce costs and waste, and avoid risks at the operational stage of the project.

A cross-industry analysis of DT functions highlights sector-specific trends. Behavioral models and decision-making simulations dominate in supply chains, reflecting the complexity of coordinating multiple stakeholders and predicting product flows across the network. In contrast, geometrical and physical modeling is more prevalent in construction and photovoltaic sectors, where accurate representation of physical assets is critical for reuse, recycling, and structural optimization. Manufacturing focuses primarily on real-time data collection and monitoring at the micro level to support operational efficiency, waste reduction, and predictive maintenance. These patterns indicate that the choice of DT function is closely linked to the Circular Economy priorities and operational challenges of each industry, providing insights for future research on tailored DT applications. Table 2 not only

categorises DT functions by sector and Circular Economy level but also reveals patterns in their application, suggesting that sector-specific requirements and Circular Economy priorities influence the selection of DT functions.

To reduce the descriptive nature of architectural analysis and enable cross-industry comparison, DT implementations identified in this review can be interpreted through a maturity-based taxonomy that reflects increasing levels of intelligence and autonomy in supporting Circular Economy practices.

At the first maturity level, DTs primarily function as a monitoring-based systems. These DTs rely on real-time data acquisition and support condition monitoring. Such implementations are common in early-stage manufacturing and construction applications, where DTs are mainly used for data transparency and operational awareness.

The second maturity level corresponds to predictive and analytical DTs, where data-driven and behavioral models are employed to forecast system performance, anticipate failures. At this level, DTs support decision-making related to maintenance planning, disassembly strategies, and material recovery. Most manufacturing and supply chain DT applications reviewed in this study fall within this category.

The third maturity level comprises prescriptive and semi-autonomous DTs that integrate decision-making or rule-based models to recommend optimised actions. These DTs move beyond prediction by actively supporting Circular Economy-oriented decisions, although human oversight remains central.

Finally, a fourth, emerging maturity level can be identified, characterized by autonomous or self-adaptive DTs capable of closed-loop optimization and dynamic reconfiguration. This maturity-based taxonomy clarifies how DT architectures evolve from data-centric tools to intelligent, decision-oriented systems and provides a structured lens for comparing DT adoption across industries in relation to Circular Economy objectives.

Digital Twin Architecture in the Circular Economy

The DT structure is primarily composed of the physical layer, digital layer, and network layer. Across all industries, sensor networks, and database integration are commonly used for data collection at the physical layer. The physical layer includes the real-world system, processes, and IoT devices or sensors used to collect data throughout the lifecycle. The network layer ensures connectivity between the physical and digital worlds through communication protocols (e.g., AutomationML, OPC-UA), middleware, and programming interfaces that enable real-time data transmission. Finally, the digital layer hosts different types of models—geometric, physical, behavioral, collaborative, and decision-making models—that replicate or simulate the behavior of the system and support Circular Economy-oriented decisions, such as reuse, recycling, or predictive maintenance. Some papers suggest the use of RFID technology, which highlights the effectiveness of sensor systems but does not explore other data collection methods. In the construction industry, tools such as BIM, VR, and three-dimensional scanners are used to collect data on the geometric structure of the product or system being digitally replicated [73,79]. However, in the manufacturing context, sensor networks are the most useful. The network layer is mainly accountable for connecting the physical and digital layers via these networks: Middleware (specifically, Service Oriented Architecture), programming interfaces, Communication protocol/interface (Automation ML), Communication protocol, and Wireless communication. The communication protocol allows the physical system to collect and exchange information in real time with the digital layer [44]. For instance, in the supply chain industry, the network layer of the DT can enhance data exchange, where the supply chain network is mirrored through a network of interconnected DTs, and each DT represents a particular phase in the supply chain [83]. In the manufacturing industry, wireless communication can connect the DT layers wirelessly, thus, improving the flexibility in data transmission in a manufacturing/production site. Wireless communication has a broader coverage area of communication and provides more stable connections compared to other methods. Programming interfaces facilitate communication and enable monitoring and control of the product or system.

In the digital layer, several models are employed to evaluate and replicate the behavior of the physical system [44]. These models include data-driven models, geometry models, behavioral models, physical models, collaborative information models, and rule/decision-making models. The utilization of data-driven models allows the manufacturing industry to extract valuable insights and make informed decisions about the condition of their products or systems. This leads to enhanced manufacturing operations and reliability of decision-making processes, especially when it comes to recovery or remanufacturing planning. Similarly, in the PV industry, data-driven methods can be used to analyze power consumption and identify any unwanted gas emissions [86]. A physical model can be used to calculate the deformation of a product during its end-of-life stage or at any stage to determine whether its useful life can be extended. This process provides valuable information about the product's status, enabling informed decisions to be made on whether to recycle, reuse, remanufacture, or repair it. A geometry model can identify product deviations and aid in the reconditioning of a product, as the DT can run simulations to test several possible geometries [62]. Specifically in terms of construction, the geometry model can

validate the geometrical structure and identify any potential defects and wastes for better accuracy in the building structure [79]. The geometry model in the PV industry is used to assist in the creation of a new PV plant, in such cases, the design and construction of the plan is simplified [85]. The decision-making model in the DT simplifies the decision-making process in the manufacturing industry. Similarly, the decision-making model in the PV industry can help identify which PV components should be disposed of or reused in another PV plant. A behavior model shows the manner in which the driving factors govern the physical system. In supply chain applications, the efficiency of the supply chain can be improved via the use of a behavioral model in which a DT monitors, simulates, and evaluates its own behavior [36]. This enables the identification of trends or issues that can then be addressed. For manufacturing or production purposes, a DT can evaluate a system's behavior instantaneously using a behavior model. This simulates and evaluates the behavior and performance of a manufacturing system. A collaborative model simulates the behaviour of multiple assets working together, providing a more comprehensive simulation of supply chain operations, particularly in logistics, where multiple assets are involved. The combination of these tools and methods enables the DT to closely emulate its real counterparts.

Table 3 presents the network and digital layers of the DT across different applications. Manufacturing applications predominantly rely on sensor networks and data-driven decision models to support operational optimisation and remanufacturing. Supply chain DTs emphasise collaborative information models and behavioural simulations to model complex networks of actors, whereas in photovoltaics the focus remains exploratory, with data-driven decision-making models applied to PV panel lifecycle management. Construction applications emphasise geometric and BIM-based models for material traceability and design for disassembly, whereas supply chain applications focus more on behavioural and collaborative models to coordinate multiple stakeholders. Manufacturing DTs rely heavily on sensor networks, AutomationML protocols, and decision-making models to optimize production and disassembly processes. These differences suggest that the choice of DT architecture is closely tied to sector-specific circularity priorities, from real-time efficiency in manufacturing to design optimization and reuse in construction.

Based on the analyzed papers, the most prominent DT architecture is found in the manufacturing and construction industries. While applying DT to enhance the Circular Economy in the supply chain is possible, it is constrained by limitations such as real-time data collection and data security [81]. Similarly, in the photovoltaic industry, the capabilities of DTs to support Circular Economy are still preliminary, with proper DT architectures yet to be fully developed or validated. These findings indicate that applications in these sectors remain exploratory, and further empirical research is needed to establish robust, practical frameworks. Combining methods and models across DT layers could provide a comprehensive approach to assess the complete DT architecture for each application context. As a result, Figures 3–5 illustrate the DT architecture for the manufacturing/production industry, construction industry, and supply chain industry, respectively.

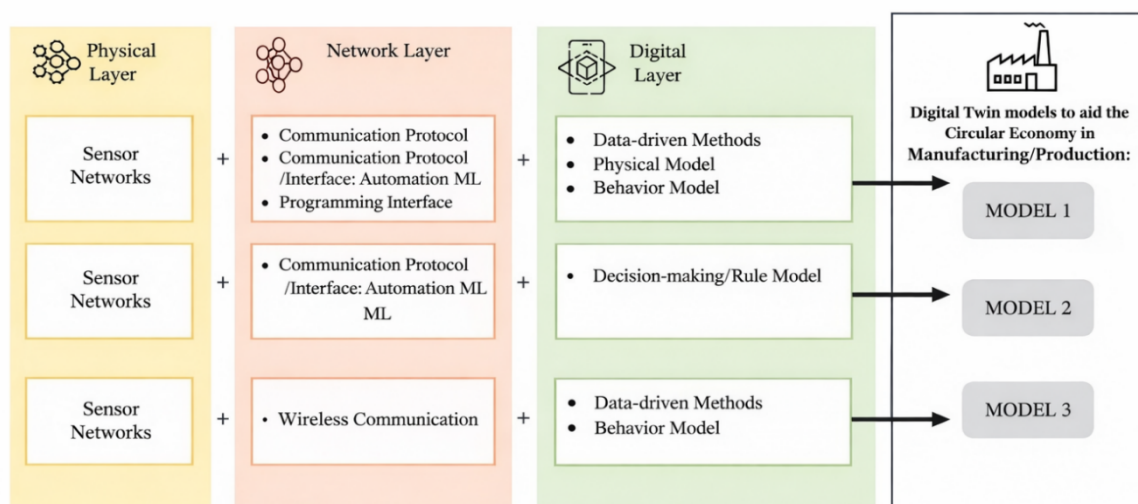


Figure 3. DT architecture in manufacturing/production.

Table 3. DT layers and the advantages of the combination of tools used in the published work.

Application Context	DT Layers	Combination of Tools	Purpose and Advantages	Ref.	
Manufacturing/production	Network layer	<ul style="list-style-type: none"> • Communication protocol/interface: automation ML • Wireless communication 	<ul style="list-style-type: none"> • Track carriers and product flow in real time • Distinguish new vs. reconditioned products 	[62]	
		<ul style="list-style-type: none"> • Communication protocol • Communication protocol/interface: automation ML • Programming interfaces 	<ul style="list-style-type: none"> • Enable real-time data access and integration • Synchronize physical and virtual environments • Support optimized disassembly planning via MES 	[69]	
	Digital layer	<ul style="list-style-type: none"> • Geometry model • Collaborative information model • Decision-making/ rule model 	<ul style="list-style-type: none"> • Manage material and information flows • Detect volumetric deviations • Support reconditioning decision-making 	[62]	
		<ul style="list-style-type: none"> • Data-driven models • Physical model • Behaviour model 	<ul style="list-style-type: none"> • Simulate system behaviour and energy performance • Analyse operational data • Support data-driven decision-making 	[69]	
		<ul style="list-style-type: none"> • Data-driven models • Behaviour model 	<ul style="list-style-type: none"> • Model system behaviour and environment • Enable closed-loop simulation • Support performance optimisation 	[60]	
		<ul style="list-style-type: none"> • Data-driven models • Decision-making/ rule model 	<ul style="list-style-type: none"> • Extract and analyse DT data • Enable autonomous decision-making • Optimize recovery and process operations 	[70,87]	
		<ul style="list-style-type: none"> • Behaviour model • Decision-making/rule model 	<ul style="list-style-type: none"> • Simulate process behaviour • Support process monitoring and optimisation • Improve resource efficiency and cascade use 	[67]	
		<ul style="list-style-type: none"> • Middleware: service-oriented architecture • Wireless communication • Programming interfaces 	<ul style="list-style-type: none"> • Standardize data structures • Enable lifecycle data streaming • Support stakeholder interaction with DT 	[75]	
	Construction	Network layer	<ul style="list-style-type: none"> • Communication protocol • Communication protocol/interface: automation ml • Wireless communication • Programming interfaces 	<ul style="list-style-type: none"> • Enable cross-organizational data sharing • Improve collaboration across stakeholders 	[72]
			<ul style="list-style-type: none"> • Middleware: service-oriented architecture • Programming interfaces 	<ul style="list-style-type: none"> • Integrate waste-related data • Support multi-software interoperability 	[78]

Table 3. Cont.

Application Context	DT Layers	Combination of Tools	Purpose and Advantages	Ref.
Construction	Digital layer	<ul style="list-style-type: none"> • Data-driven models • Physical model • Behaviour model • Decision-making/rule model 	<ul style="list-style-type: none"> • Support decision-making in construction processes • Evaluate cost and waste scenarios • Optimize sustainability strategies 	[78]
		<ul style="list-style-type: none"> • Data-driven models • Geometry model • Decision-making/rule model 	<ul style="list-style-type: none"> • Replicate building structure (BIM-based) • Support design, renovation, and demolition decisions • Identify waste and reusable materials 	[79,80]
Supply chain	Network layer	<ul style="list-style-type: none"> • Communication protocol • Wireless communication 	<ul style="list-style-type: none"> • Enable distributed DT communication • Define and manage data streams across the network 	[83]
	Digital layer	<ul style="list-style-type: none"> • Data-driven models • Behaviour model • Decision-making/rule model 	<ul style="list-style-type: none"> • Monitor product status and lifecycle data • Support behavioural analysis • Optimize material and product flows 	[36]
		<ul style="list-style-type: none"> • Data-driven models • Collaborative information model • Decision-making/ rule model 	<ul style="list-style-type: none"> • Extract knowledge from data-driven models • Enable DT-to-DT communication • Synchronize decision-making across the network 	[83]
Photovoltaic	Digital layer	<ul style="list-style-type: none"> • Data-driven models • Decision-making/ rule model 	<ul style="list-style-type: none"> • Model system input–output relationships • Simulate lifecycle performance • Support decision-making for resource optimisation 	[85]

Figure 3 illustrates the DT architecture for the manufacturing/production sector. At the physical layer, multiple sensor networks are deployed to store operational data from machines, processes, and products. This real-time information is transmitted through the network layer, which relies on communication protocols, Automation ML interfaces, and wireless communication technologies to ensure seamless data transfer between the physical and digital environments. At the digital layer, the collected data are processed and modeled using different approaches. Data-driven and behavioural models enable monitoring machine performance and predicting failures, while physical models replicate production processes for scenario analysis. Decision-making and rule-based models support automated planning, enabling optimal disassembly sequences, remanufacturing strategies, and material recovery. The integration of these three layers yields DT models that support Circular Economy strategies by extending product lifecycles, enhancing resource efficiency, and reducing waste in manufacturing.

Figure 4 presents the DT architecture for the construction sector. The structural layers are the same; however, data-driven methods provide real-time insights into material usage and performance, while geometric models (e.g., BIM and 3D scans) replicate the structure of buildings and infrastructure with high accuracy. Collaborative information models enable the integration of multiple stakeholders' inputs, ensuring transparency in material tracking and project data. Finally, decision-making and rule-based models support the selection of sustainable design alternatives, planning for disassembly, and strategies for reusing or recycling construction materials.

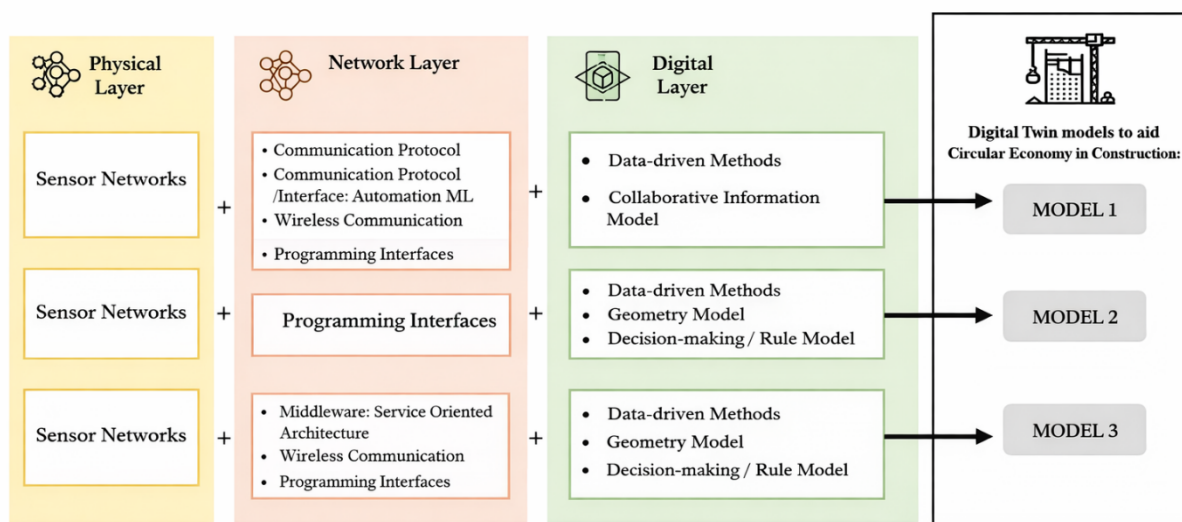


Figure 4. DT architecture in construction.

Figure 5 illustrates the DT architecture for the supply chain sector. In this case, collaborative information models enable integration across multiple stakeholders, ensuring that decisions on reuse, remanufacturing, or recycling are based on consistent, transparent data. The combination of these layers leads to DT models that facilitate Circular Economy strategies in supply chains by improving visibility, optimizing logistics, reducing waste, and fostering greater collaboration among producers, recyclers, and consumers.

Based on the assessed papers, the manufacturing industry, a DT architecture is commonly composed of wireless sensor networks, data-driven models, behavioral models, and decision-making/rule models [60,69]. In the construction industry, the framework suggested by the papers is unique, and can be adapted based on the complexity of the construction application. However, some common methods used are geometric models and data-driven methods [72,75,80]. In the supply chain industry, only one paper discussed a full DT architecture, and it includes data-driven models, decision-making models, and collaborative information models [83]. The papers discussing the applications of the DT in the photovoltaic industry did not discuss the actual architecture of the DT. Instead, the papers focused on how the DT promotes the Circular Economy of a PV system. These papers proposed the use of programming interfaces, decision-making models, and data-driven models [84,85]. However, there was no indication of which method to use in the physical layer for real-time data collection.

Finally, the architectural analysis addresses RQ3 by explaining how DT layers and models are configured to support Circular Economy implementation.

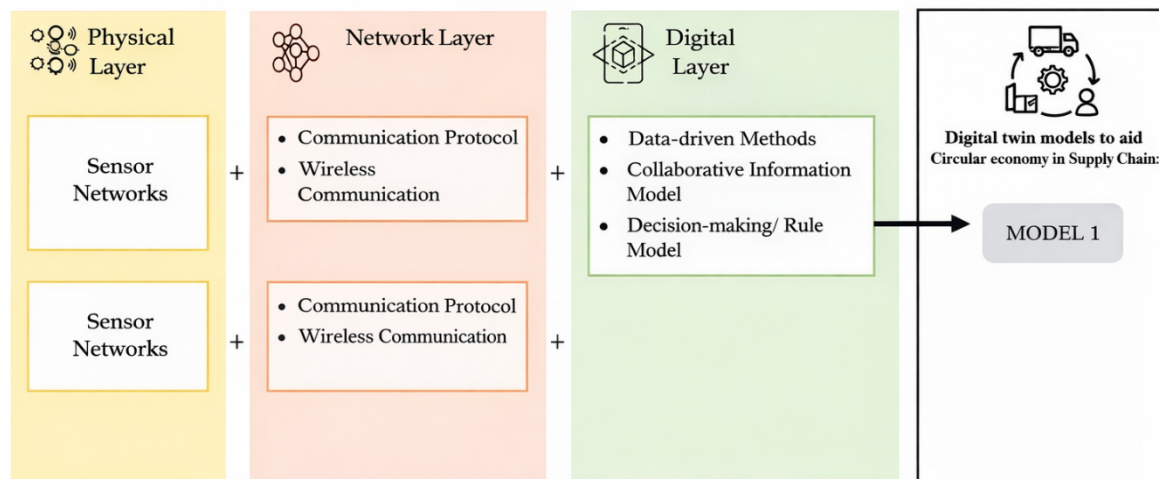


Figure 5. DT architecture in supply chain.

5. Discussion on Cross-Sector Challenges and Research Question

The analysis of the reviewed literature provides a structured understanding of how DT technologies are currently applied to support Circular Economy practices across different contexts.

RQ1: the findings show that DT applications are predominantly concentrated in manufacturing and construction, where the need for resource optimization, waste reduction, and lifecycle monitoring is most critical. In contrast, applications in photovoltaic systems and supply chain contexts remain comparatively limited, indicating emerging but still underdeveloped research areas. Importantly, supply chain DTs are not confined to a single sector but operate as cross-cutting systems that enable coordination and data exchange across multiple industries and lifecycle stages.

RQ2: the results highlight that DTs primarily perform functions related to data collection, monitoring, simulation, and decision support. These functions are strongly aligned with operational Circular Economy activities such as reuse, recycling, and remanufacturing. However, higher-level functions—such as strategic planning, eco-design integration, and systemic optimization—are rarely addressed. This indicates that current DT implementations largely support operational efficiency rather than enabling transformative Circular Economy models.

RQ3: the architectural analysis reveals a common three-layer structure (physical, network, digital) across all sectors. While the physical and digital layers are generally well developed, the network layer remains comparatively underexplored, particularly in terms of interoperability, standardization, and secure data exchange. This architectural imbalance represents a key limitation for scaling DT solutions across multiple stakeholders and lifecycle stages. Many studies remain focused on the micro level—the product or single process—while few explore applications at larger scales, such as industrial districts or eco-parks. Moreover, while the physical and digital layers of DTs are usually well described, the network layer—the one intended to guarantee standardised, secure data exchange—often remains underdeveloped.

Beyond technological and architectural challenges, policy enablers play a pivotal role in accelerating DT-CE integration. For example, Extended Producer Responsibility (EPR) schemes incentivize manufacturers to ensure product traceability and recovery at end-of-life, directly aligning with DT capabilities for lifecycle monitoring and predictive decision-making [87]. Similarly, the European Commission's proposal for Digital Product Passports (DPP) under the EU Circular Economy Action Plan standardizes data on material composition, repairability, and recyclability, thereby facilitating interoperability and transparency in DT applications [88]. Embedding such regulatory frameworks into DT architectures can enable firms not only to comply with regulations but also to leverage DTs as strategic tools for collaboration with recyclers, consumers, and policymakers. This suggests that DT adoption will advance more rapidly in jurisdictions with strong regulatory drivers (e.g., EPR, DPP, eco-design directives) [19].

6. Conclusions and Future Work

This paper presented a comprehensive literature review on the integration of DTs and Circular Economy across various industries, addressing three research questions: (1) in which application contexts DTs are implemented; (2) which DT functions are employed to promote Circular Economy; and (3) how DT architectures

facilitate Circular Economy principles. The analysis shows that most DT applications focus on micro- and macro-level activities, primarily in manufacturing and construction, with an emphasis on reusing and recycling processes. Theoretically, this study contributes by clarifying sector-specific patterns in DT functions and their alignment with Circular Economy priorities, and by highlighting underexplored areas, such as meso-level applications and eco-design integration. Practically, it identifies how DTs can enable data-driven decision-making, lifecycle monitoring, and stakeholder collaboration to enhance circularity.

Despite this study's contributions, several critical research gaps remain. First, there is a clear lack of real-world validation of Digital Twin implementations for Circular Economy applications, as most studies remain conceptual or prototype-based, limiting their practical scalability and industrial adoption. Second, existing research is heavily concentrated at the micro level, with meso-level applications—such as eco-industrial parks and interconnected circular systems—remaining largely unexplored, highlighting a significant gap in systemic circularity. Third, persistent challenges in data integration and interoperability across Digital Twin layers and stakeholders hinder the development of fully connected, scalable DT ecosystems, particularly in multi-actor environments such as supply chains and construction. Addressing these gaps is essential for advancing Digital Twin research from isolated applications toward integrated, real-world Circular Economy systems.

Building on these insights, future research should prioritize: (1) testing DT applications across all Circular Economy levels and lifecycle stages; (2) developing measurable indicators for circularity performance; (3) investigating integration with complementary digital technologies; and (4) formulating testable hypotheses to guide empirical studies. By addressing these directions, DT research can move from conceptual proposals to actionable solutions, bridging theoretical understanding with practical implementation.

Author Contributions

C.S.: methodology, conceptualization, supervision, software, writing—reviewing and editing.; S.J.A.B.: data curation, writing—original draft preparation, investigation, visualization; H.A.: investigation, visualization, writing—reviewing and editing; M.C.: writing—reviewing and editing, investigation, software, validation; M.D.: validation, supervision, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

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